A GRAND DESIGN SPIRAL GALAXY WITH AN INTERACTING COMPANION: N5194 and N5195

NASA Grant NAG5-1881

Final Report

For the Period 15 December 1989 through 14 May 2000

Principal Investigator
Dr. Christine Jones

May 2000

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. Robert Petre, Code 666, Laboratory for High Energy Astrophysics, Space Science Directorate, Goddard Space Flight Center, Greenbelt, Maryland 20771.

Under the grant NAG5-1881 6A87, we studied the X-ray emission from galaxies, clusters, and gravitational lenses as observed by ROSAT.

In addition to several invited and contributed talks presented at conferences, the following papers (listed with their abstracts) that are published in refereed journals were completed as part of this activity –

"Mass to Light Ratios of Groups and Clusters of Galaxies" V. Hradecky, C. Jones, H. Donnelly, S.G. Djorgovski, R. Gal, and S. Odewahn Atrophysical Journal, submitted

We constrain the mass-to-light ratios, gas mass fraction and the ratio of total to luminous mass for a sample of 8 relaxed galaxy groups and clusters: A262, A426, A478, A1795, A2052, A2063, A2199, and MKW4s. We use ASCA spacially resolved spetroscopic X-ray observations and ROSAT PSPC images to constrain the total and gas masses of these clusters. To measure cluster luminosities we use galaxy catalogs resulting from the digitization and automated processing of the second generation Palomar Sky Survey plates calibrated with CCD images in the Gunn-thuan g, r, and i bands.

Assuming H_0 = 65 km/sec/Mpc, the measured mass-to-light ratios are about 130. This, along with a high baryonic fraction, is indicative of a low density universe with Omega 0.15–0.2.

"SN Ia Enrichment in Virgo Early-Type Galaxies from ROSAT and ASCA Observations A" A. Finoguenov and C. Jones Astrophysical Journal, accepted.

We analyzed nine X-ray bright Virgo early-type galaxies observed by both the ASCA and ROSAT. Through spatially resolved spectroscopy, we determined the radial temperature profile and abundances of Mg, Si and Fe for six galaxies. The temperature profiles are consistent with isothermal temperatures outside of a cooler region at the galaxy center. We present new evidence for iron abundance gradients in NGC4472 and NGC4649 and confirm the previous results on NGC4636. Mg and Si abundance gradients on average are flatter compared to those of iron and correspond to an underabundance of alpha-process elements at high Fe values, while at low iron, the element ratios favor enrichment by type II SNe. We explain the observed trend by the metallicity dependence of SN Ia metal production and present constraints on the available theoretical modeling for low-metallicity inhibition of SNe Ia (Kobayashi et al. 1998). Our results imply a cut-off metallicity in the range 0.07–0.3 solar and require a lower limit of 0.3 solar on the Fe contribution of SN Ia. We estimate a SN Ia rate at the centers of the brightest galaxies in our sample of $\sim 0.05 h_{75}^3$ SNU. The rates inferred from optical searches values should be corrected for the presence of "faint" SN Ia events, since these release limited metals and therefore are not found through the X-ray emission. With this correction the present-day SN Ia rate in early-type galaxies is $0.10 \pm 0.06\ h_{75}^2$ SNU (Capellaro et al. 1997) and is therefore comparable with the X-ray estimates.

"Asymmetric, arc minute scale structures around NGC 1275" E. Churazov, W. Forman, C. Jones, and H. Bohringer Astronomy and Astrophysics 356, 788

ROSAT HRI observations show complicated substructure in the X-ray surface brightness within 5 arcminutes around NGC 1275 - the dominant galaxy of the Perseus cluster. The typical amplitude of the variations is of the order of 30brightness at a given distance from NGC 1275. We argue that this substructure could be related to the activity of NGC 1275 in the past. Bubbles of relativistic plasma, inflated by jets, being forced to rise by buoyancy forces, mix with the ambient intracluster medium (ICM), and then spread. Overall evolution of the bubble may resemble the evolution of a hot bubble during a powerful atmospheric explosion. From a comparison of the time scale of the bubble inflation to the rise time of the bubbles and from the observed size of the radio lobes which displace the thermal gas, the energy release in the relativistic plasma by the active nucleus of NGC 1275 can be inferred. Approximate modeling implies a nuclear power output of the order of 1045 erg s-1 averaged over the last 3 107 years. This is comparable with the energy radiated in X-rays during the same epoch. Detailed measurements of the morphology of the X-ray structure, the temperature and abundance distributions with Chandra and XMM may test this hypothesis.

"Outer Regions of the Cluster Gaseous Atmospheres" A. Vikhlinin, W. Forman, and C. Jones Astrophysical Journal Vol 525, pg 47.

We present a systematic study of the hot gas distribution in the outer regions of regular clusters using ROSAT PSPC data. Outside the cooling flow region, the β-model describes the observed surface brightness closely, but not precisely. Between 0.3 and 1 virial radii, the profiles are characterized by a power law with slope, expressed in terms of the β-parameter, in the range $\beta = 0.65 - 0.85$. The values of β in this range of radii are typically larger by 0.05 than those derived from the global fit. There is a mild trend for the slope to increase with temperature, from $< \beta > \approx 0.68$ for 3 keV clusters to 0.8 for 10 keV clusters; however, even at high temperatures there are clusters with flat gas profiles, $\beta < 0.7$. Our values of β at large radius are systematically higher, and the trend of β with temperature is weaker than was previously found; the most likely explanation is that earlier studies were affected by an incomplete exclusion of the central cooling flow regions. For our regular clusters, the gas distribution at large radii is quite close to spherically symmetric, and this is shown not to be an artifact of the sample selection. The gas density profiles are very similar when compared in units of the cluster virial radius. The radius of fixed mean gas overdensity 1000 (corresponding to the dark matter overdensity 200 for $\Omega = 0.2$) shows a tight correlation with temperature, R T0.5, as expected from the virial theorem for clusters with the universal gas fraction. At a given temperature, the rms scatter of the gas overdensity radius is only 7%, which translates into a 20% scatter of the gas mass fraction, including statistical scatter due to measurement uncertainties.

"Constraining q_0 with Cluster Gas Mass Fractions: A Feasibility Study" K. Rines, W. Forman, U. Pen, C. Jones, and R. Burg Astrophysical Journal Vol 517, pg 70.

As the largest gravitationally bound objects in the universe, clusters of galaxies may contain a fair sample of the baryonic mass fraction of the universe. Since the gas mass fraction from the hot intracluster medium is believed to be constant in time, the value of the cosmological deceleration parameter q_0 can be determined, in principle, by comparing the calculated gas mass fraction in nearby and distant clusters. To test the potential of this method, we compare the gas fractions derived for a sample of luminous ($L_X > 10^{45}$ ergs s^{-1}) nearby clusters with those calculated for eight luminous distant ($0.3 < z < 0.6$) clusters using ASCA and ROSAT observations. For consistency, we evaluate the gas mass fraction at a fixed physical radius of 1 h_{50}^{-1} Mpc (assuming $q_0 = 0.0$). We find a best-fit value of $q_0 = 0.07$ with $-0.47 < q_0 < 0.67$ at 95% confidence. This analysis includes both measurement errors and an intrinsic 25% scatter in the gas fractions due to the effects of cooling flows and mergers. We also determine the gas fraction using the method of Evrard, Metzler, and Navarro to find the total mass within r_{500}, the radius where the mean overdensity of matter is 500 times the critical density. In simulations, this method reduces the scatter in the determination of gravitational mass without biasing the mean. We find that it also reduces the scatter in actual observations for nearby clusters but not as much as simulations suggest. Using this method, the best-fit value is $q_0 = 0.04$ with $-0.50 < q_0 < 0.64$. The excellent agreement between these two methods suggests that this may be a useful technique for determining q_0. The constraints on q_0 should improve as more distant clusters are studied and precise temperature profiles are measured to large radii.

"X-ray Detection of the Primary Lens Galaxy Cluster of the Gravitational Lens System Q0957+561", G. Chartas, D. Chuss, W. Forman, C. Jones, and I Shapiro. Astrophysical Journal Vol 504, pg 661.

Analysis of several recent ROSAT High-Resolution Imager (HRI) observations of the gravitationally lensed system Q0957+561 has led to the detection at the 3 sigma level of the cluster lens containing the primary galaxy G1. The total mass was estimated by applying the equation of hydrostatic equilibrium to the detected hot intracluster gas for a range of cluster core radii, cluster sizes, and for different values of the Hubble constant. X-ray estimates of the lensing cluster mass provide a means to determine the cluster contribution to the deflection of rays originating from the quasar Q0957+561. The present mass estimates were used to evaluate the convergence parameter kappa , the ratio of the local surface mass density of the cluster to the critical surface mass density for lensing. The convergence parameter kappa , calculated in the vicinity of the lensed images, was found to range between 0.07 and 0.21, depending on the assumed cluster core radius and cluster extent. This range of uncertainty in kappa does not include possible systematic errors arising from the estimation of the cluster temperature through the use of the cluster luminosity-temperature relation and the assumption of spherical symmetry of the cluster gas. Applying this range of values of kappa to the lensing model of Grogin & Narayan for Q0957+561 but not accounting for uncertainties in that model yields a range of values for the Hubble constant: $67 < H0 < 82$ km s^{-1} Mpc^{-1}, for a time delay of 1.1 yr.

"X-ray Emission from the Fornax Cluster" C. Jones, C. Stern, W. Forman, J. Breen, L. David, W. Tucker, and M. Franx Atrophysical Journal 482, 143.

We have analyzed the ROSAT PSPC observations of the central region of the Fornax cluster, a relatively poor group of galaxies at a distance of about 24 Mpc. The brightest X-ray and optical galaxy in the group is NGC1399, an E1 galaxy located near the center of the Fornax cluster. We characterize the hot gas around the galaxy, derived from a $2''$ to $18''$ annulus around NGC1399, as having a mean temperature of 1.30 ± 0.05 keV and a heavy element abundance of 0.6 ± 0.1 with respect to solar (Fe/H $= 4.68 \times 10^{-5}$ by number). Spatially resolved spectral data provide both gas temperature and gas abundance profiles extending to 125 kpc ($18''$) from the galaxy. The temperature distribution, combined with the X-ray surface brightness profile, yields an accurate determination of the gravitating mass within 125 kpc which falls in the range from $4.3 - 8.1 \times 10^{12}$ $M_{\odot}$ (95% confidence range including systematic uncertainties). If we include the extended optical halo around NGC1399, the mass-to-light ratio increases with radius from 33 (± 8) at 18 kpc to 70 (± 22) at 110 kpc. We compare the heavy element abundance distribution measured around NGC1399 with that measured around the Virgo galaxy NGC4472, as well as to models for hot coronae. We find that the abundance distribution is in good agreement with that previously measured for NGC4472 (Forman et al. 1993). For both galaxies, the observed abundance profiles require a weak evolution of the type Ia supernova rate with time and a present epoch rate which agrees with that of Cappellaro et al. (1993).

We compare mass measurements in NGC1399 to those for M87. The similarity of the optical masses in these systems and their differences in gas masses and gravitating masses, lead us to suggest that the optical galaxies formed at an early stage when the central potentials of these two systems were similar. Subsequent infall of gas and dark matter into the larger, deeper Virgo potential resulted in the greater mass of the Virgo cluster compared to Fornax.

We also report on X-ray properties of thirteen other Fornax galaxies. Eight of these were detected in ROSAT images with luminosities in the 0.2 to 2 keV energy band from 1×10^{39} to 1.6×10^{41} ergs sec. Five galaxies were sufficiently bright to permit spectral analyses and all but one (NGC1380) had spectra consistent with thermal emission. Two (NGC1404 and NGC1387) of the four galaxies with well-constrained spectral parameters have hot coronae with characteristic gas temperatures of about 0.5 keV and iron abundances less than that found around NGC1399 and other bright ellipticals. To maintain these hot coronae, the absolute magnitudes of these galaxies must be brighter than -19. Thus the distance to Fornax must be at least 18 Mpc, and, if there are not large peculiar velocities, the Hubble constant should be less than 75 km sec^{-1} Mpc^{-1}. Since these galaxies are all members of Fornax, distance uncertainties do not effect the relationship between their optical magnitude and X-ray luminosity. Analysis of the Fornax galaxies supports the contention that the scatter in the X-ray and optical relationship is intrinsic and does not arise solely from distance uncertainties. For the elliptical galaxy NGC1404, the X-ray images show that the hot corona is distorted and likely is being stripped, indicating infall of the galaxy toward NGC1399 and the cluster center.

"An X-ray and Optical Study of Clusters in Formation" M. Henrikseon and C. Jones Astrophysical Journal Vol 465, pg 666.

We present an analysis of observations by the ROSAT Position Sensitive Proportional Counter (PSPC) of subclusters in bimodal systems A3395 (SC 0627-54) and A3528 (SC 1252-28). The best-fit temperatures range from 2 to 4 keV and are the first temperature measurements for this class of objects. The gas is detected out to 300 kpc (A3395) and 650 kpc (A3528) from the center of the subclusters, but this is likely not the full extent of the gas. Therefore, we have determined masses for the subclusters, assuming the gas is isothermal, of $\sim 1.0 \times 10^{14}$ h_{75}^{-1} M_{sun} within 0.5 Mpc and $\sim 2.1^{14}$ h_{75}^{-1} M_{sun} within 1.0 Mpc. The average baryon fraction in gas is 0.09 $h_{75}^{3/2}$ within 0.5 Mpc and ~ 0.14 $h_{75}^{3/2}$ within 1.0 Mpc. The average baryon fraction in gas is consistent with the central regions of rich, evolved clusters and suggests that the merger process does not appreciably increase the gas baryon fraction. The velocity dispersion of each subcluster is comparable to that found for rich clusters. The masses we have calculated from the optical data using three different estimators are larger than those from the X-ray data because of the larger velocity dispersion of the subclusters. Since the velocity dispersions are comparable to the difference in the mean velocities because of the Hubble flow, we have imposed a radial cutoff; this reduces, but does not remove, the conflict between the optically and X-ray-derived masses, suggesting that the galaxy velocity dispersions are contaminated by the component of radial infall along the line of sight. A dynamical analysis of the A3395 cluster using the X-ray-determined masses indicates that the subclusters will fully merge in 0.3-1.2 Gyr; this is consistent with an early stage of merger which is implied by the elongation of the X-ray emission perpendicular to the merger axis resulting from the collision of the hot atmospheres. If the merger product has a mass similar to the sum of the individual subclusters, then the merger product will be a low-mass rich cluster, which is strong support for rich clusters forming from the "bottom up." Extending the dynamical analysis to include the cluster SC 0625 - 53 (A3391), which is ~ 2.8 $h_{75}^{-1}1$ Mpc away in projection, suggests that this cluster and the A3395 cluster form a bound, infalling system if they have again as much mass beyond 1 Mpc as within that radius. The improved spectral and - spatial resolution of the ROSAT PSPC allows a determination of the cooling time in the central region of the subclusters. The subcluster cooling times are slightly longer than 10 Gyr, the nominal age of the cluster atmosphere, suggesting that cooling flows with mass accretion rates similar to nearby clusters are not present during this premerger stage or that they have been disrupted. Small cooling flows on the order of a few solar masses are not ruled out.

"ROSAT Observations of the Gravitationally Lensed Quasar 0957+561" G. Chartas, E. Falco, W. Forman, C. Jones, R. Schild, and I. Shapiro, Astrophysical Journal 445, 140.

Observations of 0957+561 with the Einstein High Resolution Imager (HRI) in 1979 May and 1979 November and with the ROSAT HRI in 1991 May and 1992 October reveal large variations in the X-ray fluxes for images A and B which significantly differ from simultaneously observed changes of the corresponding optical continuum emission. Most striking was the apparent increase by over fivefold in the flux of image B from the late 1970's to the early 1900's. Further, in the 1990's the X-ray flux for image A increased by a factor of 1.7 +/- 0.3 and that of B by a factor of 1.9 +/- 0.2 between the two ROSAT observations (separated by 540 days), whereas optical measurements showed nearly no changes for A and B between these epochs. No significant changes in X-ray emission were observed on timescales of hours to days. Of we adopt 1.5 yr as the difference between the propagation time from the quasar to us via the two images ('time delay'), then the ratio of the X-ray flux of image B for the 1992 October epoch to that of A for the 1991 May epoch is 2.7 +/- 0.4. This ratio is significantly greater than the ratio of 1.05 +/- 0.03 observed in the optical R band, 0.75 in the broad line region (BLR), and 0.76 +/- 0.03 in the radio (VLBI lambda 13 cm core) for approximately the same epoch. The wavelength dependence in the ratio of the fluxes of the two images suggests that either microlensing may be significant for the X-ray band or the time delay is substanially different from 1.5 yr (and the intrinsic variation of the quasar emission were significant within an interval comparable to the uncertainty of the time delay), or both.